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A Versatile Link for high-speed, radiation resistant optical transmission in LHC upgrades

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Abstract

The Versatile Link project is developing a general purpose physical layer optical link with high bandwidth, radiation resistance and magnetic-field tolerance that meets the requirements of LHC upgrade experiments. This paper presents recent work on system specifications, front-end transceiver prototypes, passive components studies and commercial back-end transceiver evaluations.

System optical power budgets are specified for single mode (1310nm) and multi-mode (850nm) links, with a target data rate of 4.8 Gbps and a transmission length of 150 meters. Noise and interference penalties are simulated using the 10GbE link model and verified by bit error ratio measurement on reference links. The power margin is particularly constrained by radiation degradation of the front-end receivers. We report the power budgets for all link variants where at least 1.8 dB safety margins are maintained. The Versatile Transceiver (VTRx) - the front-end module to be installed on-detector - is based on a commercial small form pluggable (SFP+) package, modified to optimize size and mass, assembled to host a qualified laser, PIN photodiode, custom-designed radiation tolerant laser driver and receiving amplifier. A set of VTRxs with validated components have been prototyped and compliance tested. We also present the radiation test results on front-end components and passive components. The total fluence tests for lasers and PINs have been carried out with pions and neutrons up to 4 x 10^{15}/cm^2. SEU tests have been performed on PIN photodiodes and the full receiver optical subassembly. Radiation induced absorption in a number of single mode and multi-mode fibers, at -25°C and up to 500 kGy, have been measured and high performance candidates identified. Commercial off-of-the-shelf parts have been examined for use as back-end transceivers. Compliance tests on SFP+, 4+4 parallel optical engines and SNAP 12 transmitter/receivers have been completed.

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1. Introduction

1.1. Overview of optical links in high energy physics (HEP) experiments

Optical links are widely proposed in the design of data acquisition systems (DAQ) for the next generation of HEP experiments. Huge amount of data generated by detectors are to be transferred from the front-end electronics to the remote processing stations. The read-out link design is a common task although faces various requirements set by the different experiments.

While copper still offer design and integration flexibility at the short interconnect level, extended links at intermediate range and above are largely replaced by fiber optics, which offer higher bandwidth over greater distances. The benefits of fiber links also include high electromagnetic field resistance, lower power consumption and lightweight cabling. Another important advantage of fiber links is the removal of grounding issues [1].

Nowadays, the modularized electrical to optical converters commonly known as electro-optical transceivers are ubiquitously implemented for storage network (i.e. Fiber Channel) and data communication (i.e., Ethernet) applications with excellent cost and performance ratio. A portfolio of products varying by application, form factor, light source, operating wavelength and fiber type etc. are readily available. For comparison, three types of modules are listed in table 1 by different light sources.

Vertical cavity surface emitting laser (VCSEL) emitting at 850nm is one of the popular technologies due to low cost and low drive current. VCSEL couples well into inexpensive multi-mode fiber (MMF). Its modulation bandwidth has improved to beyond 2000 MHz.km over recent years to enable high data rate transmission at short distance. Fabry-Perot (FP) laser and distributed feedback (DFB) laser emitting at 1310nm or 1550nm are often coupled into single-mode fiber (SMF) and can reach longer distances. 1310 nm VCSEL offering the promise of both low power consumption and high bandwidth is also an interesting option.

Table 1. Types of laser source used in optical links

Source type	Operating λ(nm)	Suitable fiber	Launch power	Detection type	Data rate	cost	application
VCSEL	850 1310	MMF SMF	-3 dBm	GaAs InGaAs	10 Gbps	Low	LAN, metro Premises
FP	1310	SMF	0 dBm	InGaAs	10 Gbps	Med	LAN, metro Access
DFB	1310 1550	SMF	10 dBm	InGaAs	>10 Gbps	High	WAN, metro, long haul

Optical links have in fact long been deployed in the current generation detector DAQ systems [2-5]. For example, 40k channels of 100 MHz analog optical links using single-mode edge emitting lasers are installed in the CMS tracker readout; 20k channels of 40 Mbps digital optical links using multi-mode VCSELs and arrays are installed in the ATLAS SCT readout while 2k channels of 1.6 Gbps VCSEL links are installed in the ATLS LAr readout. In these systems, especially in the tracker area, the optical link components have to operate in high radiation environment. Sufficient radiation hardness of the light sources, fibers and PIN diodes up to the full LHC dose and fluence level has been demonstrated. In light of the experience gained from these optical link installations, it is realized that establishing common radiation hardness and reliability verification procedures as well as common test benches would help avoiding redundant efforts. It is also realized that a compact transmitter/receiver package with both standard electrical and optical interfaces would seem to be a preferred solution.

New experiments or upgrades will impose even more stringent demands on data bandwidth and radiation tolerance. For example the proposed LHC upgrade would increase luminosity by factor of 10 to 10^{35} $cm^{-2}s^{-1}$. Advanced trigger schemes are also proposed which will drive a more than 10 fold increase in the need for data bandwidth. While different link systems were independently developed in the past by each LHC experiment due to technological limitations by the requirements of the individual applications, given the rapid advances of optoelectronics and CMOS technologies, it is now possible to develop a general purpose optical link which can cover most transmission applications: a Versatile Link.

1.2. Versatile Link project overview

The Versatile Link project [6] aims to provide a multi-gigabit per second optical physical data transmission layer for the readout and control of High Luminosity LHC experiments. A point-to-point bidirectional system architecture is proposed for which components are currently being assessed and developed, as shown in Fig 1. The Versatile Link operates at a nominal data rate of 4.8 Gpbs over at least 150 meters (the distance between detector and counting room with routing) with bit error ratio of 10^{-12} or better.

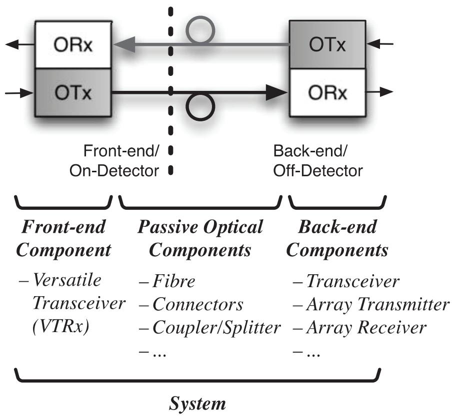


Fig. 1. The Versatile Link architecture.

The link components consist of electro-optical transceivers, fiber cables and other passive components such as connectors. The Versatile Transceiver (VTRx) is placed on detector, at the front-end. The standard transceiver (TRx) is placed off detector, at the back-end. The link supports single-mode (SM) operation with a center-wavelength of 1310nm as well as multi-mode (MM) operation with a center-wavelength of 850nm. The fiber cables are commercial SMF and laser optimized MMF respectively. The link is naturally bi-directional. But matching the number of front-end to back-end (uplink) and back-end to front-end (downlink) transmissions is not a requirement. More data will likely be transmitted from front-end to back-end. It is therefore possible to have multi-channel transmitters or receivers in the system.

Depending on the wavelength of operation and direction of data flow, four link variants are shown in Fig 2. Transmission characteristics and device families of each are listed in table 2.

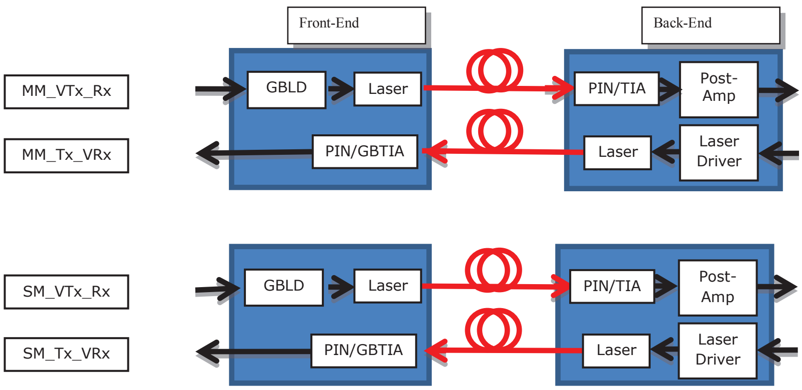


Fig. 2. The Versatile Link variants (GBLD and GBTIA are radiation tolerant ASIC supplied by CERN GBT project)

Table 2. Versatile Link characteristics and device families

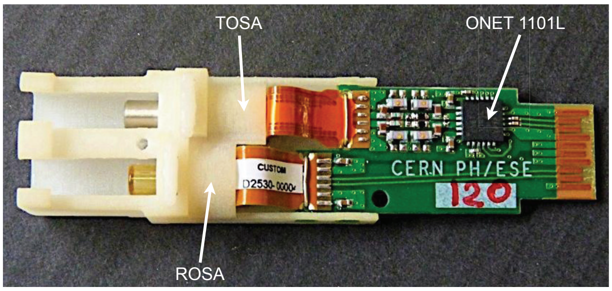
Link Variants	Transmission	VTRx	Note	TRx
MM_VTx_Rx	MM uplink	GBLD+850VCSEL	850nm MMF	10GBASE-SR 40GBASE-SR4 100GBASE-SR10 Enhanced SNAP12 Opto Engine
MM_Tx_VRx	MM downlink	GBTIA+GaAs PIN GBTIA+InGaAs PIN		
SM_VTx_Rx	SM uplink	GBLD+1310FP GBLD+1310VCSEL	1310nm SMF	10GBASE-LR 40GBASE-LR4 Enhanced SNAP12 Opto Engine
SM_Tx_VRx	SM downlink	GBTIA+InGaAs PIN		

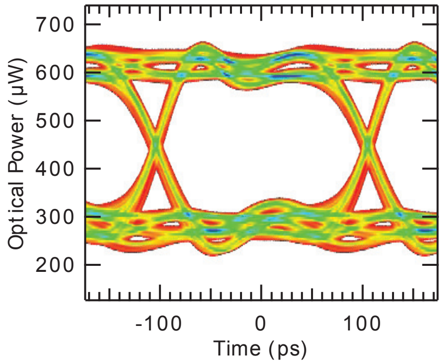
Components situated on the detectors at the front-end (VTRx and the first meters of fiber cables) must meet the strict requirements imposed by the operational environment for radiation field, lower temperature, low mass and volume. The radiation environment is particularly challenging. To balance cost and performance, the Versatile Link is developed in two radiation-tolerance classes. Calorimeter grade link is qualified to at least 10 kGy (Si) dose and 5 x 10^{14} n/cm^2 fluence (1MeV neutron equivalent) while tracker grade link is qualified to at least 500 kGy and 2 x 10^{15} n/cm^2.

2. VTRx development

The VTRx is the transceiver module that will be placed close to the upgraded SLHC detector elements at the front-end. It is a module that is based closely on a standard SFP+ transceiver in terms of electrical- and optical interfaces as well as overall dimensions. The VTRx does however need to be minimally customized for use in the SLHC detector environment: to ensure sufficient radiation tolerance, the chipset used in the VTRx has been custom designed as part of the GBT project [7]; the active opto-electronic components have been evaluated for their radiation tolerance; and finally the mechanical interface to the optical fibre connector has been re-designed to reduce its mass and remove magnetic material. In addition to the customization effort, we have developed the required testing procedures to enable the functional testing and validation of the complete VTRx.

A fully assembled VTRx is shown in Fig. 3(a). The VTRx does not have the microcontroller that is typically present on a commercial SFP+ module. The user is thus required to set the laser bias and drive currents in order to achieve the desired system performance. Initial versions of the VTRx have been prototyped with commercially available laser drivers – the ONET1101L edge-emitter and ONET8501V VCSEL drivers – coupled to either a Fabry-Pérot laser diode operating at 1300 nm or a VCSEL operating at 850 nm for SM and MM use respectively.





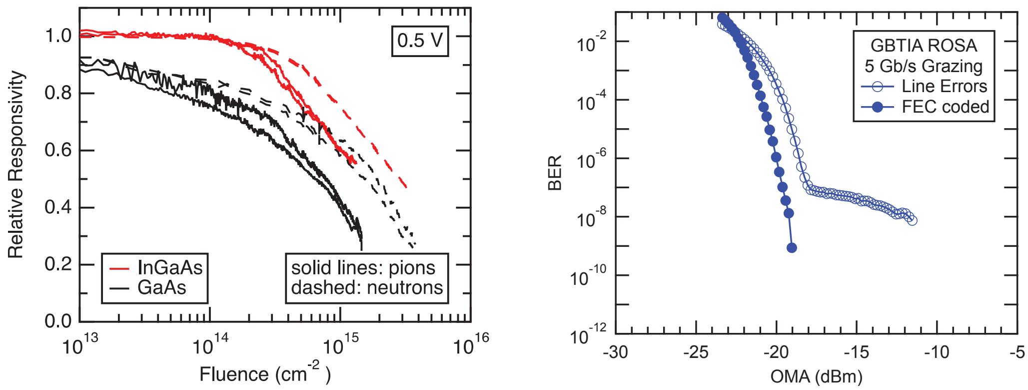
(a) (b)

Fig. 3 Showing a fully assembled VTRx (left) comprising Transmitter- and Receiver Optical Sub-Assemblies (TOSA and ROSA), PCB with laser driver (ONET1101L) and optical connector block. The attendant optical output eye diagram (right) when operating at the GBT line rate of 4.8 Gb/s is also shown.

Fig. 3(b) shows a typical eye diagram of the edge-emitter based VTRx that uses a commercial laser driver. The eye diagram measurement allows us to quantify the performance in terms of both amplitude and jitter, which are compared to the specifications that have been derived from the Ethernet and Fibre Channel specifications scaled to the target line rate of 4.8 Gb/s. A standard test suite for both transmitter and receiver has been developed to allow these measurements to be made.

It has long been established that laser diodes subjected to particle irradiation show an increase in threshold current and attendant decrease in output slope efficiency [8,9]. However, due to the complexity of the semiconductor heterostructures used in modern laser diodes, it is necessary to carry out radiation testing in order to assess the damage to a particular candidate device. Since the situation is similar for photodiodes, we have carried out an extensive test programme of both lasers and photodiodes to find devices suitable to be used in the VTRx. We have tested a broad spectrum of devices using both neutron and pion beams in order to be confident that the devices will survive the SLHC lifetime fluence levels. Single-event effect testing has also been carried out on candidate photodiodes and ROSA assemblies. Fig. 4(a) shows the particle-induced drop in responsivity of two representative photodiodes. The observed trend clearly shows that the drop in responsivity must be accounted for in the system power budget as it is significant. Furthermore, it shows that it might – depending upon the target application – be advantageous to use InGaAs photodiodes for multimode links operating at 850 nm as this will lead overall to a lower power penalty since the damage is less for the InGaAs devices. Fig. 4(b) shows the Bit Error Rate induced by a particle beam in a prototype ROSA built with a commercial InGaAs photodiode and the custom-designed receiving amplifier (GBTIA). The induced error rate is clearly not acceptable for system operation, hence the inclusion of a Forward Error Correction (FEC) code in the GBT chipset.

Fig. 4(b) also shows the effectiveness of the FEC as the particle-induced errors are fully corrected and the BER is below 10^{-9}. Full details of the GBT coding scheme and the radiation testing carried out to date can be found in [10].



(a) (b)

Fig. 4. (a) The effect of 180 MeV pion and 20 MeV neutron irradiation on the responsivity of InGaAs and GaAs photiodiodes. (b) The Bit Error Rate induced by a 60 MeV proton beam with a flux of 2x108 p/cm2/s in the GBTIA-based ROSA.

3. Fiber and passive components

Since both 850 nm and 1310 nm operations are accommodated within the Versatile Link project, both single-mode (SMF) and multimode (MMF) optical fibers are under investigation. In the multi-mode case, the fiber bandwidth should be sufficient for data transfer at a rate of 5-10 Gbps over lengths of up to 150 m. This mandates a migration from legacy step-index MMF to graded index fibers. The radiation hardness of these fibers (both OM3 and OM4 standards) needs to be confirmed.

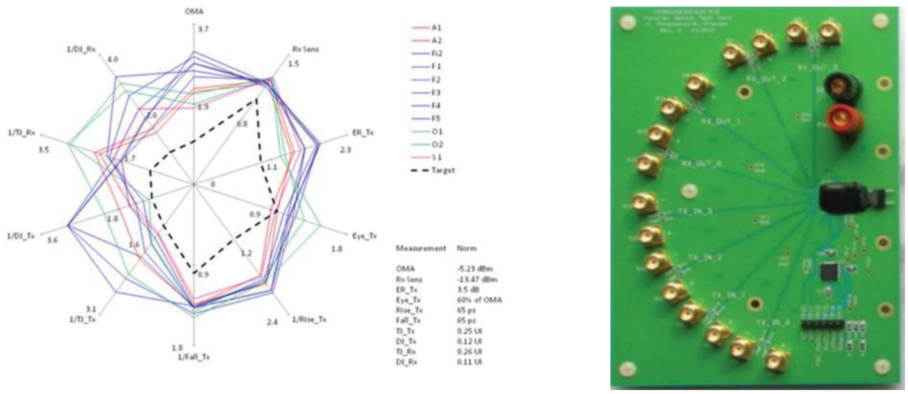
Radiation Induced Absorption (RIA) of optical fiber is highly dependent on the dose rate and temperature of the environment. Given an equal integrated dose, fibers suffer greater RIA when that dose is delivered at a higher rate. They also suffer a greater RIA at lower temperatures compared to higher temperatures. Since many detector locations are actively cooled, radiation tests on fiber RIA need to be done with cooled fibers. The first tests at -25 deg. C at 27 kGy(Si)/hr showed mixed results where some of the SMF candidates appeared to have acceptable RIA but all of the MMF candidates experienced attenuations greater than the dynamic range of the test equipment [11]. In order to qualify for deployment, the passive link must suffer less than 1.0 dB of overall RIA for the tracker area and 0.05 dB or less for the calorimeter.

The mechanical integrity of fibers, cables, and connectors is also under investigation. Tensile strength, micro-bending, and insertion loss tests are performed pre- and post-irradiation up to 500 kGy(Si). The results thus far have shown negligible degradation. Post-radiation fiber bandwidth tests have demonstrated less than 10% degradation which still meets our system requirements.

4. Standard back-end transceivers

Back-end transceivers will not be subject to the harsh requirements that must be met by the front-end components. As a result these are selected from the best candidates identified from commercial vendors. They need to be evaluated to ensure that they meet the overall requirements of the system as they must be capable of working successfully with the VTRx discussed above. Devices investigated include mature single channel transceivers, upcoming array transmitters and receivers, and as per system requirement, high optical transmitting power modules in a few particular cases which will be discussed in section 5. Fig 6(a) shows the spider chart for evaluated commercial SFP+ modules to be used in single-mode calorimeter grade links. The dotted line indicates the specification for the Versatile Link back-end transceivers, which has been met by the majority of tested modules.

At present a number of preliminary standards (i.e. parallel transceiver) and custom products (i.e. optical engine) are emerging in the array product category. For the desirable features of low power and high density, a number of devices are sampled with test cards. Fig 6 (b) shows the custom design of a carrier board loaded with a 4 + 4 parallel optical engine. A SNAP12 form factor device is also tested at elevated data rate of up to 5 Gbps. Details of the test procedures and evaluation criteria are discussed in [12]. Preliminary measurements of emerging parallel components show favorable performance when compared with existing single channel SFP+ components. Further testing is underway to identify promising potential components for inclusion in the suite of recommended Versatile Link components.



(a) (b)

Fig. 6. (a) SFP+ spider chart for single-mode calorimeter variant short list, the dotted line indicates back-end component specification values. (b) Test board for the 4-array optical engine.

5. System integration

To ensure a link BER below 10^{-12} at the target data rate and length, the optical power budget must be carefully planned ahead so that an adequate receiving signal-to-noise ratio is maintained under all operation conditions. Noise and interference penalties are simulated using 10GbE link model which renders a maximum penalty of 1.0 dB for multi-mode versatile link and a maximum penalty of 1.5 dB for single-mode versatile link. These results are validated by bit error rate measurement on a number of surveyed reference links [13]. Radiation degradations of the VTRx and fibers are discussed in section 2 and 3. Fiber attenuation, connector and splice losses are also accounted for. The available powers are mostly constrained by radiation degradation of the VTRx PIN diodes, especially in the tracker area. For these links higher transmitter optical powers are required. In table 3, we report the power budgets for all link variants where at least 1.8 dB safety margins are maintained. The power allocation is rounded to 0.1dB.

Link jitter allocation and component jitter contribution are derived from Fiber Channel standards at 4.8 Gbps data rate. The prototyped VTRx samples are tested to be compliant with extra margin. Link reliability is qualitatively predicted using vendor data and standard part count method. Pending on demonstration test results against targeted environmental stresses, the Versatile Link failure rate is 500 FIT (failure per 10^9 device-hours), which is equivalent to 5% channel failure during 10 years of detector operation.

Table 3. Tracker grade and calorimeter grade link optical power budget

Tracker grade	MM_VTx_Rx	MM_Tx_VRx	SM_VTx_Rx	SM_Tx_VRx
Min. Tx OMA	-5.2 dBm	-1.6 dBm	-5.2 dBm	-3.6 dBm
Max. Rx sensitivity	-11.1 dBm	-13.1 dBm	-12.6 dBm	-15.4 dBm
Power budget	5.9 dB	11.5 dB	7.4 dB	11.8 dB
Fiber attenuation	0.6 dB	0.6 dB	0.1 dB	0.1 dB
Insertion loss	1.5 dB	1.5 dB	2.0 dB	2.0 dB
Link penalties	1.0 dB	1.0 dB	1.5 dB	1.5 dB
Tx radiation penalty	0 dB	-	0 dB	-
Rx radiation penalty	-	5.4 dB	-	5.4 dB
Fiber radiation penalty	1.0 dB	1.0 dB	1.0 dB	1.0 dB
Margin	1.8 dB	2.0 dB	2.8 dB	1.8 dB
Calorimeter grade	**MM_VTx_Rx**	**MM_Tx_VRx**	**SM_VTx_Rx**	**SM_Tx_VRx**
Min. Tx OMA	-5.2 dBm	-3.2 dBm	-5.2 dBm	-5.2 dBm
Max. Rx sensitivity	-11.1 dBm	-13.1 dBm	-12.6 dBm	-15.4 dBm
Power budget	5.9 dB	9.9 dB	7.4 dB	10.2 dB
Fiber attenuation	0.6 dB	0.6 dB	0.1 dB	0.1 dB
Insertion loss	1.5 dB	1.5 dB	2.0 dB	2.0 dB
Link penalties	1.0 dB	1.0 dB	1.5 dB	1.5 dB
Tx radiation penalty	0 dB	-	0 dB	-
Rx radiation penalty	-	2.5 dB	-	2.5 dB
Fiber radiation penalty	0.1 dB	0.1 dB	0 dB	0 dB
Margin	2.7 dB	4.2 dB	3.8 dB	4.1 dB

6. Conclusions

Optical links designed for next generation HEP experiments must meet the requirements of high data rate and stringent environmental constraints. The Versatile Link project aims to provide a general purpose physical link for the LHC upgrades. It carries out the approach of modification of standard package, qualification of commercial lasers, fibers, connectors and photodiodes as well integration of custom ASIC.

Performance compliant, low mass package is successfully validated. Integration of ASICs and optical sub-assemblies shows good results. Prototype phase of VTRx development is close to completion. Set of irradiation tests on front-end and passive components render lists of qualified components. Both single channel and parallel back-end transceivers are evaluated. System specifications based on simulation and testing are produced, which gives us confidence that the system will work on a large scale. System demonstrators will soon be available to interested users for sampling.

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